Embedded Sensor Fusion and Perception for Autonomous Vehicle

Christian Laugier

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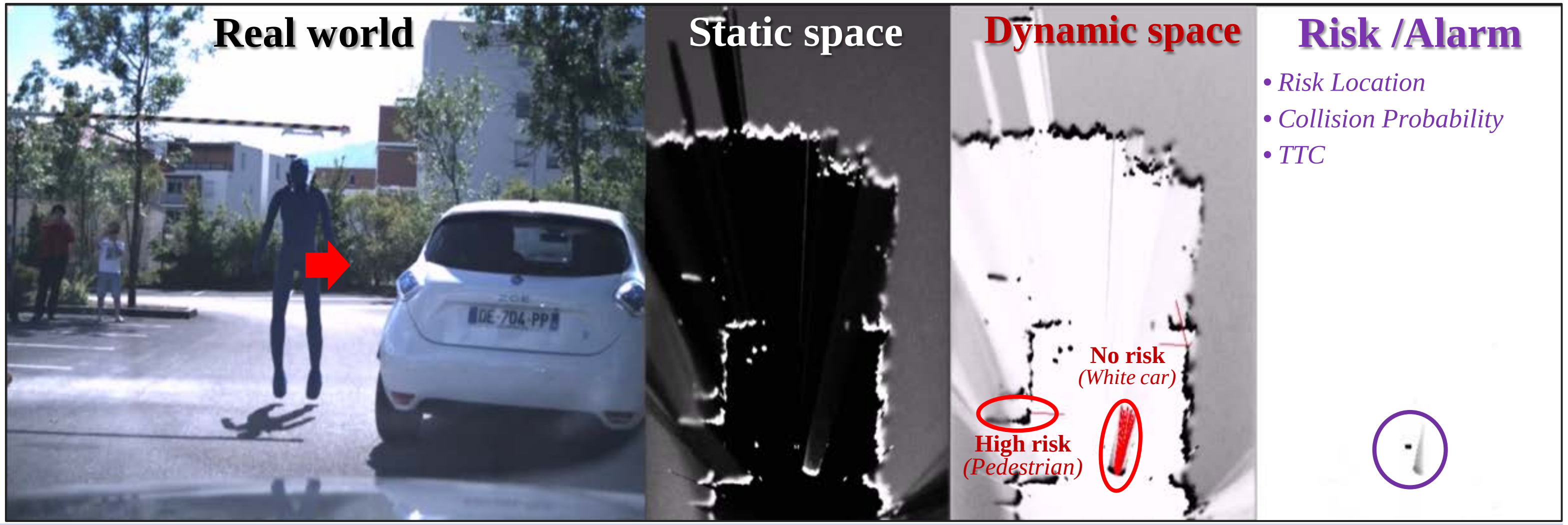


IS Auto Europe 2019
Berlin, Germany, 9-10 April 2019

Technology status & Ongoing challenges for AV

- Strong involvement of Car Industry & GAFA + Large media coverage
- An expected market of 500 B€ in 2035… *but Legal & Regulation issues still unclear*
- Technologies Validation & Certification => *Numerous experiments in real traffic conditions since 2010 (Disengagement reports ⇔ Insights on system maturity)*

=> But insufficient … Realistic Simulation & Formal methods are also needed (e.g. EU Enable-S3)

Tesla Autopilot L2 with Radar & Mobileye/Intel
Commercial ADAS product => Tested by customers !

Drive Me trials (Volvo, 2017)
- *100 Test Vehicles in Göteborg, 80 km, 70km/h*
- *No pedestrians & Plenty of separations between lanes*

Future Mobility Services

Numerous EU projects in last 2 decades
Cybus, 3 months experiment low speed La Rochelle 2012

Dense 3D mapping & Numerous vehicles
10 years R&D, 8 millions km covered since 2010 & 25 000 km/day

"Self-Driving Taxi Service" testing in US *(Uber, Waymo)* & Singapore *(nuTonomy)*

⇒ ***Autonomous Mobility Service**, Numerous Sensors + "Safety driver" during testing*
⇒ ***Uber:** System testing since 2017, Disengagement every 0.7 miles in 2017 (improved now)*
⇒ ***Waymo:** 1st US Self Driving Taxi Service launched in Phoenix in Dec 2018*
⇒ ***Disengagement reports provide insights on the technology maturity***

Millions of miles driven since 2010 (Google, Tesla, Waymo, Uber..)

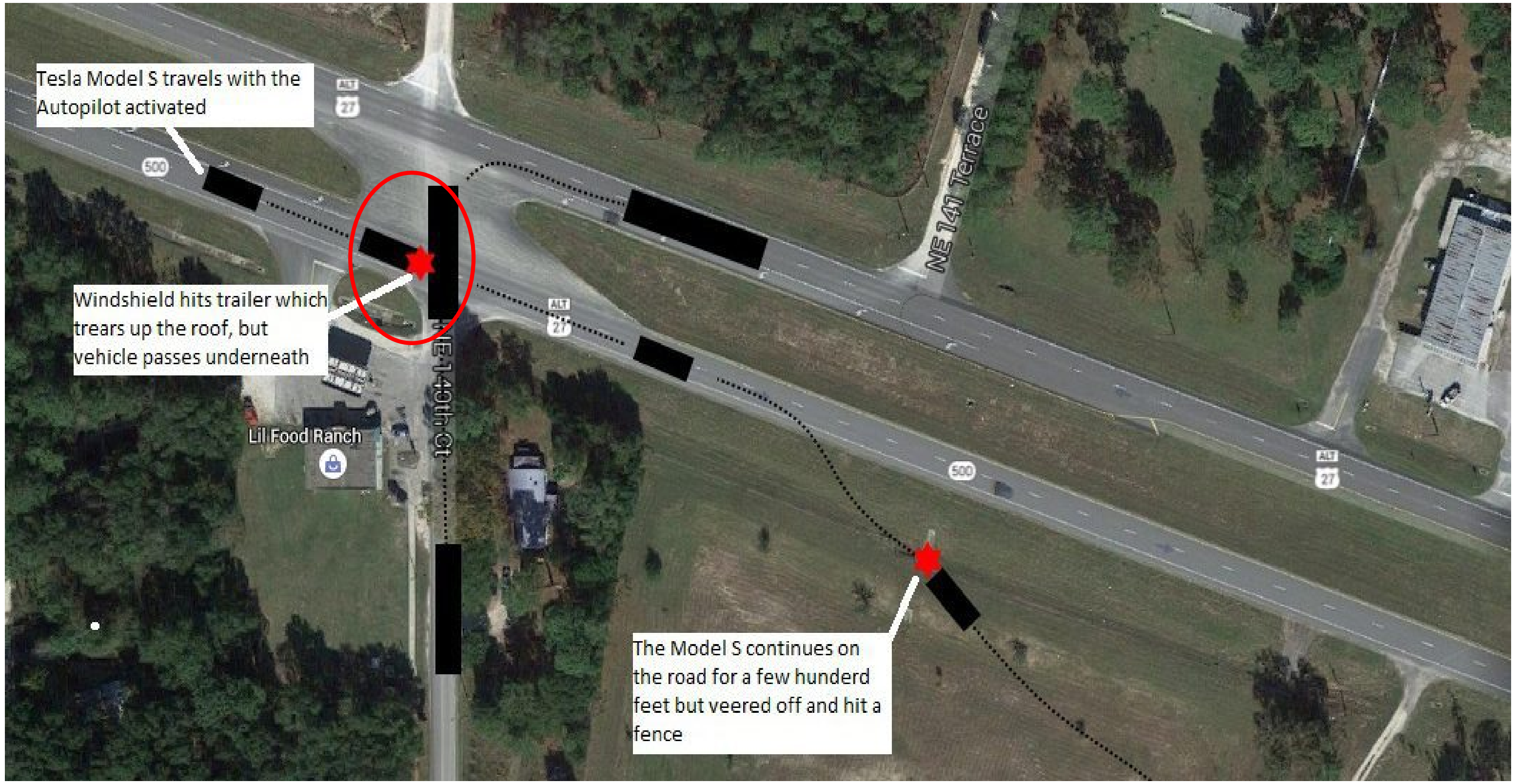
Several benign & serious accidents in past few years

Safety is still not guaranteed !

Safety issue: *Tesla Autopilot "level 2" fatal accident (May 2016)*

- **Tesla driver killed in a crash with Autopilot "level 2" active (ADAS mode)**
- **The Autopilot failed to detect a white moving truck, with a brightly lit sky**
  - ***Camera** => White color against a brightly lit sky ?*
  - ***Radar** => High height of the trailer probably confused the radar into thinking it is an overhead road sign ?*
- **The human driver was not vigilant**

Tesla Model S – Autopilot
Front perception:
Camera (Mobileye)+ Radar + US sensors



Safety issue: *Uber "level 3"AV fatal accident (March 2018)*

- **Self-driving Uber AV kills a woman in the first fatal crash involving a pedestrian**
  Temple, Arizona, March 2018

- **The vehicle was moving at 40 mph and didn't reduced its speed before the crash**
  - *Despite the presence of multiple sensors, the **perception system failed to detect the pedestrian** in a poor lighting condition*
  - *The **AV didn't disengaged***

- **The Safety Driver reacted too late** => *He was not attentive enough, and he reacted less than 1s before the crash & started to brake 1s after the crash*

Embedded Perception & Scene Understanding – *Overview*

Complex Dynamic Scenes understanding

Situation Awareness & Decision-making

⇒ *Sensing + Prior knowledge + Interpretation*

⇒ *Navigation strategy*

Perception & Decision-making for Safe Intentional Navigation

Dealing with unexpected events

e.g. Road Safety Campaign, France 2014

Anticipation & Prediction

for avoiding upcoming accidents

=>*Focus of Attention + Sensing + Collision Risk*

=> *Collision avoidance strategy*

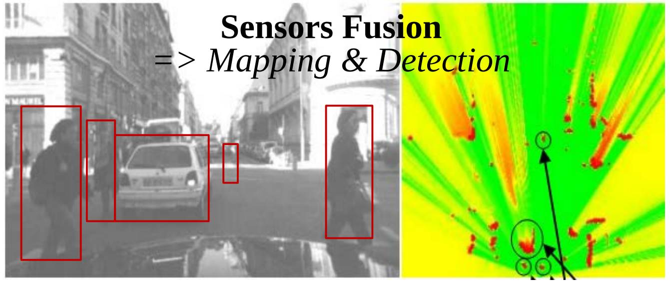
Main features

- ✓ Dynamic & Open Environments => *Real-time processing & Reactivity*
- ✓ Incompleteness & Uncertainty => *Appropriate Model & Algorithms (probabilistic approaches)*
- ✓ Sensors limitations (no sensor is perfect) => *Multi-Sensors Fusion*
- ✓ Hardware / Software integration => *Satisfying Embedded constraints*
- ✓ Human in the loop (mixed traffic) => ***Human Aware Decision-making***

  Taking into account Interactions + Behaviors + Social rules (including traffic rules)

Paradigm 1: Embedded Bayesian Perception

Embedded Multi-Sensors Perception
⇒ *Continuous monitoring of the dynamic environment*



❑ Main challenges

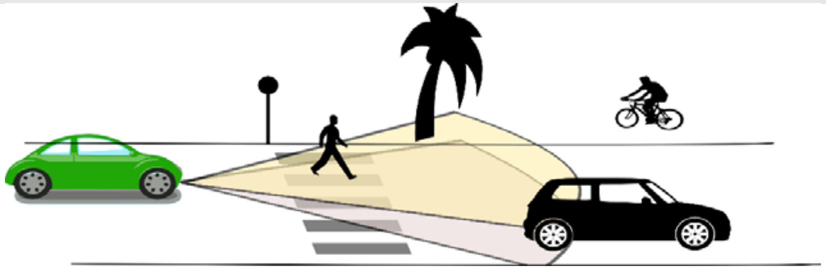
- ✓ *Noisy data, Incompleteness, Dynamicity, Discrete measurements*
- ✓ ***Strong Embedded & Real time constraints***

❑ Our Approach: Embedded Bayesian Perception

- ✓ *Reasoning about **Uncertainty & Time window** (Past & Future events)*
- ✓ ***Improving robustness** using **Bayesian Sensors Fusion***
- ✓ ***Interpreting the dynamic scene** using **Contextual & Semantic** information*
- ✓ ***Software & Hardware integration** using GPU, Multicore, Microcontrollers…*

Bayesian Perception : Basic idea

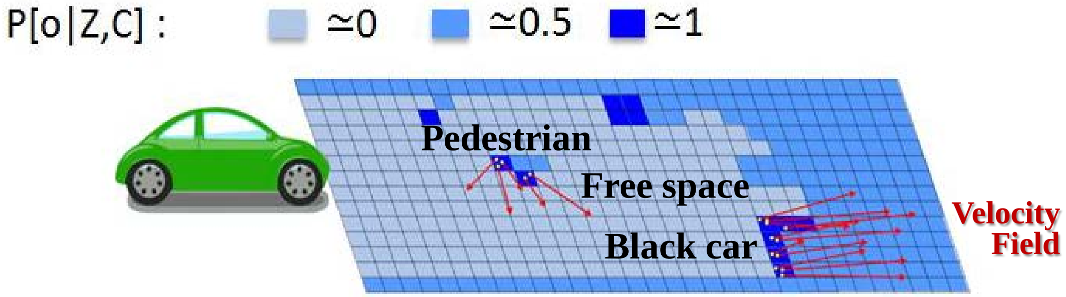
- ❑ Multi-Sensors Observations
  Lidar, Radar, Stereo camera, IMU …



Bayesian
Multi-Sensors Fusion

Real-time

- ❑ Probabilistic Environment Model
  - ✓ *Sensor Fusion*
  - ✓ *Occupancy grid integrating uncertainty*
  - ✓ *Probabilistic representation of Velocities*
  - ✓ *Prediction models*



Concept of "Dynamic Probabilistic Grid"
⇒ *Occupancy & Velocity probabilities*
⇒ *Embedded models for* ***<u>Motion Prediction</u>***

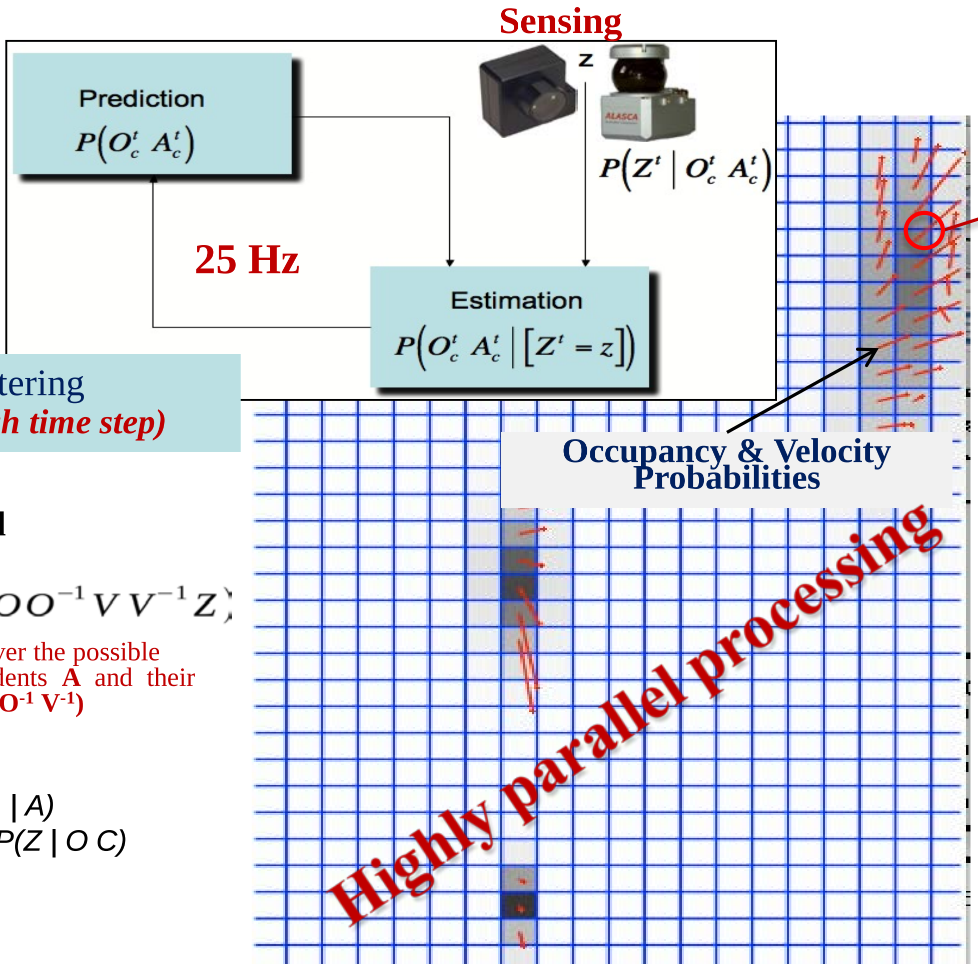
- ❑ Main philosophy
  Reasoning at the grid level as far as possible for both :
  - ***Improving efficiency*** *=> highly parallel processing*
  - ***Avoiding traditional object level processing problems*** *(e.g. detection errors, wrong data association…)*

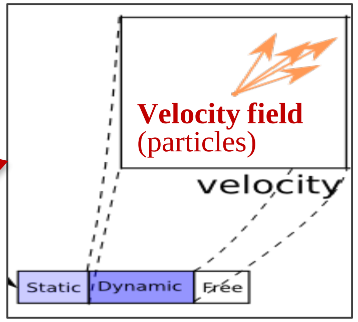
The "Dynamic Probabilistic Grids" paradigm

⇒ *A more and more popular approach for Autonomous Vehicles*
⇒ *A clear distinction between Static & Dynamic & Free components*

Pioneer concept of "Bayesian Occupancy Filter" (Inria)

[PhD Thesis Coué 2005] [Coué & Laugier IJRR 05] [Laugier et al ITSM 2011] [Laugier, Vasquez, Martinelli Mooc uTOP 2015]





Bayesian Filtering
(Grid update at each time step)

Solving for each cell

$$P(O\,V \mid Z\,C) = \lambda \sum_{A\,O^{-1}\,V^{-1}} P(C\,A\,O\,O^{-1}\,V\,V^{-1}\,Z)$$

Sum over the possible antecedents **A** and their states **(O^{-1} V^{-1})**

Joint Probability decomposition:

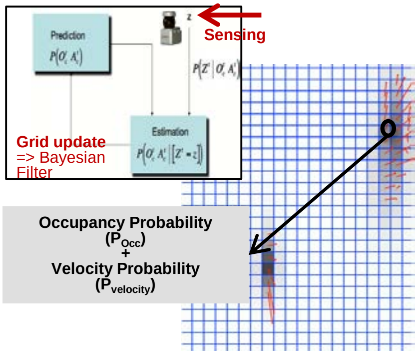
$$P(C\,A\,O\,O^{-1}\,V\,V^{-1}\,Z) = P(A)\ \ P(O^{-1}\,V^{-1} \mid A)\ \ P(O\,V \mid O^{-1}\,V^{-1})\ \ P(C \mid A\,V)\ \ P(Z \mid O\,C)$$

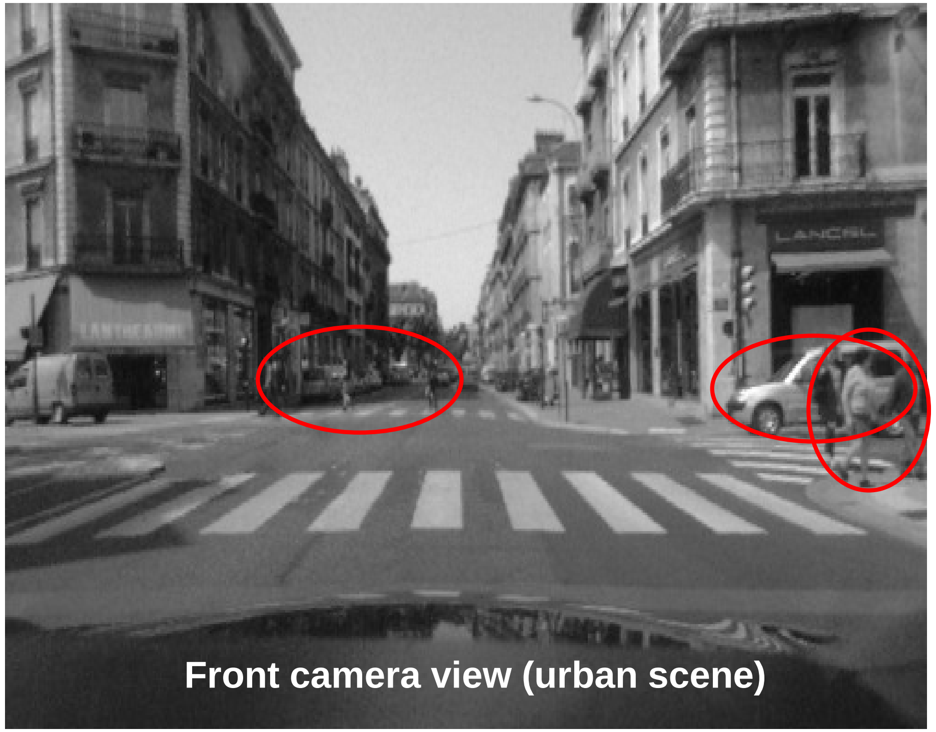
- ***Bayesian Occupancy Filter Approach***
  - *=> Patented by Inria & Probayes (2005)*
  - *=> Commercialized by Probayes*
  - *=> Robust to sensing errors & occultation*
  - *=> Appropriate for highly parallel processing*
- ***Real-time embedded implementation***
  - *=> Nvidia GPU, 2014*
- ***Used by:*** *Toyota, Denso, Probayes, Renault, EasyMile, IRT Nanoelec / CEA*
- ***Industrial licenses 2018:*** *Toyota, EasyMile*

Bayesian Occupancy Filter Approach – *Main Features*

=> Exploiting the Dynamic Information for a better understanding of the scene

- Estimate **Spatial occupancy for each cell of the grid** ***P (O | Z)***
- **Grid update** is performed in each cell in parallel *(using BOF equations)*
- **Extract Motion Field** *(using Bayesian filtering & Fused Sensor data)*
- **Reason at the Grid level** *(i.e. no object segmentation at this reasoning level)*

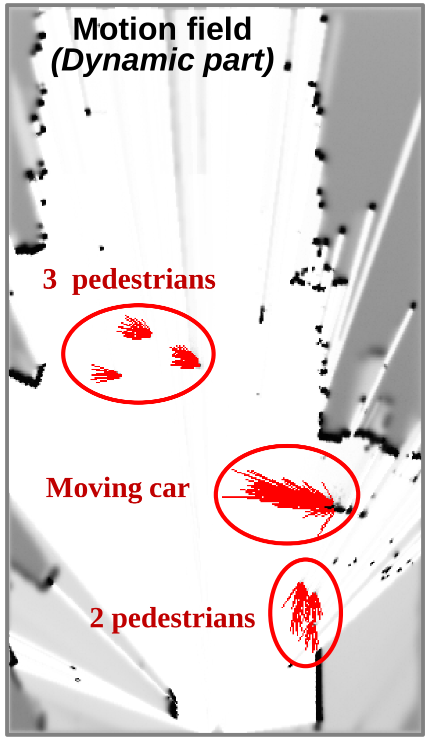




Sensors data fusion
+
Bayesian Filtering
+
Extracted Motion Fields

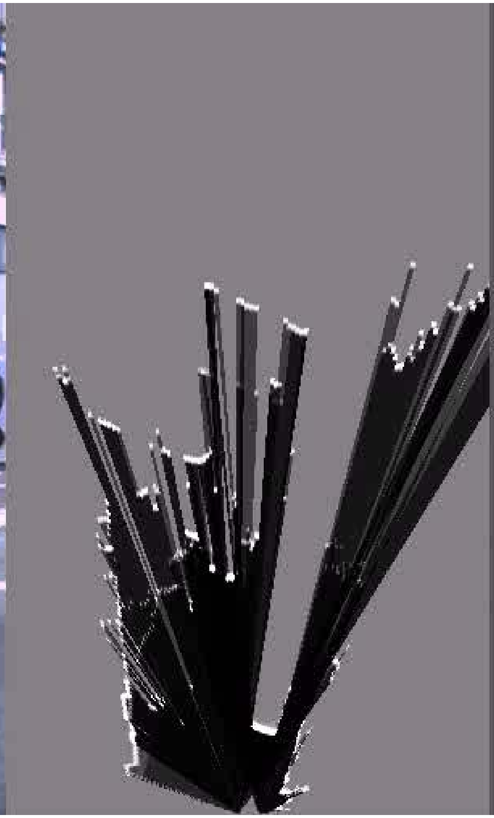
HSBOF

1st Embedded & Optimized version (patent 2014)



Experimental Results in dense Urban Environments

Observed Urban Traffic scene



Ego Vehicle *(not visible in the video)*

OG Left Lidar

OG Right Lidar

OG Fusion
+
Velocity Fields

Patented Improvements & Implementations

=> Several models & implementations more and more adapted to ***Embedded constraints & Scene complexity***

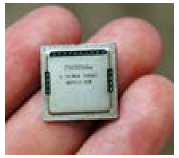
❖ Hybrid Sampling Bayesian Occupancy Filter (HSBOF, patent 2014)

[Negre et al 14]
[Rummelhard et al 14]

=> Drastic ***memory size reduction*** *(factor 100) + Increased* ***efficiency*** *(complex scenes)*
+ More ***accurate Velocity estimation*** *(using Particles & Motion data from ego-vehicle)*

❖ Conditional Monte-Carlo Dense Occupancy Tracker (CMCDOT, 2015)

[Rummelhard et al 15]

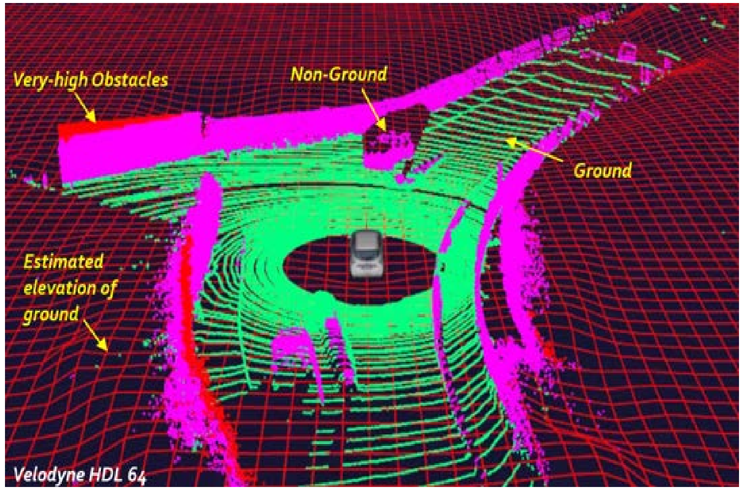


=> Increased efficiency using "state data" *(Static, Dynamic, Empty,* ***Unknown****) + Integration of a* ***"Dense Occupancy Tracker"*** *(Object level, Using particles propagation & ID)*

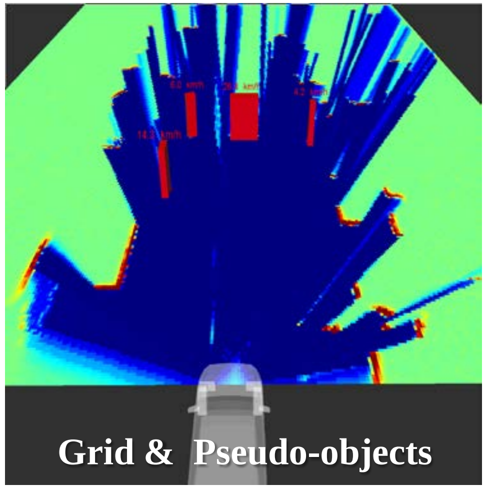
❖ CMCDOT + Ground Estimator (Patent 2017)

[Rummelhard et al 17]

=> Ground shape estimation & Improve obstacle detection *=> Avoid false detections on the ground surface*



Ground Estimation & Point Cloud Classification (2017)

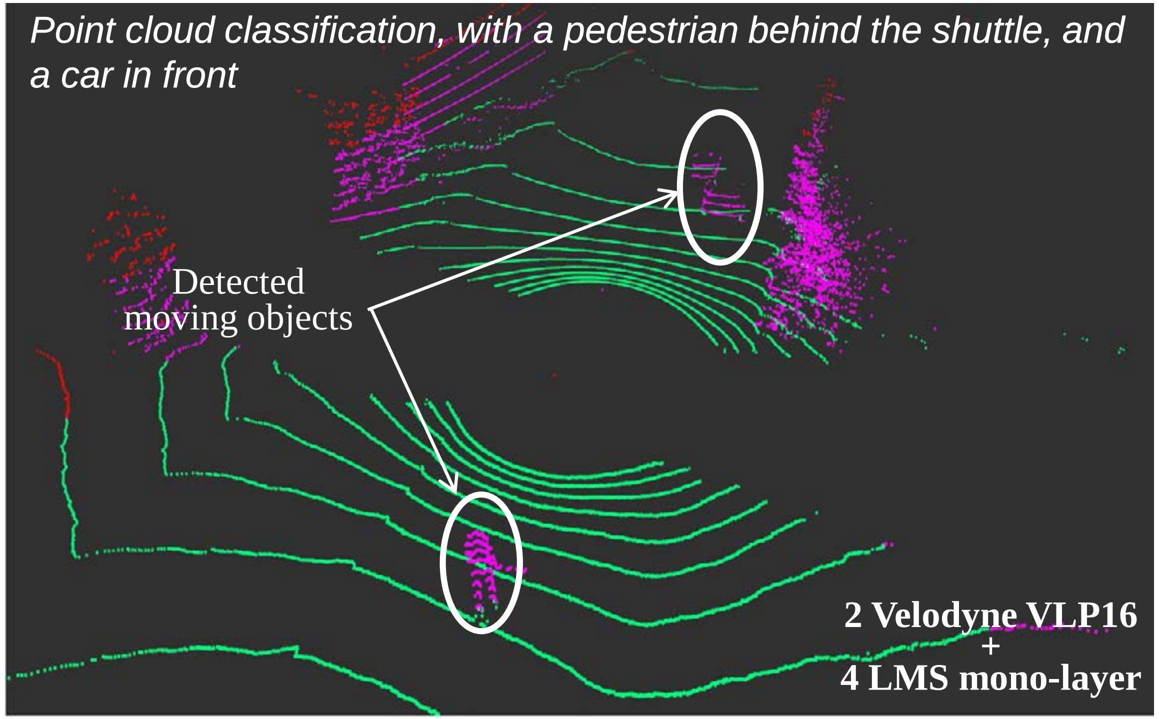


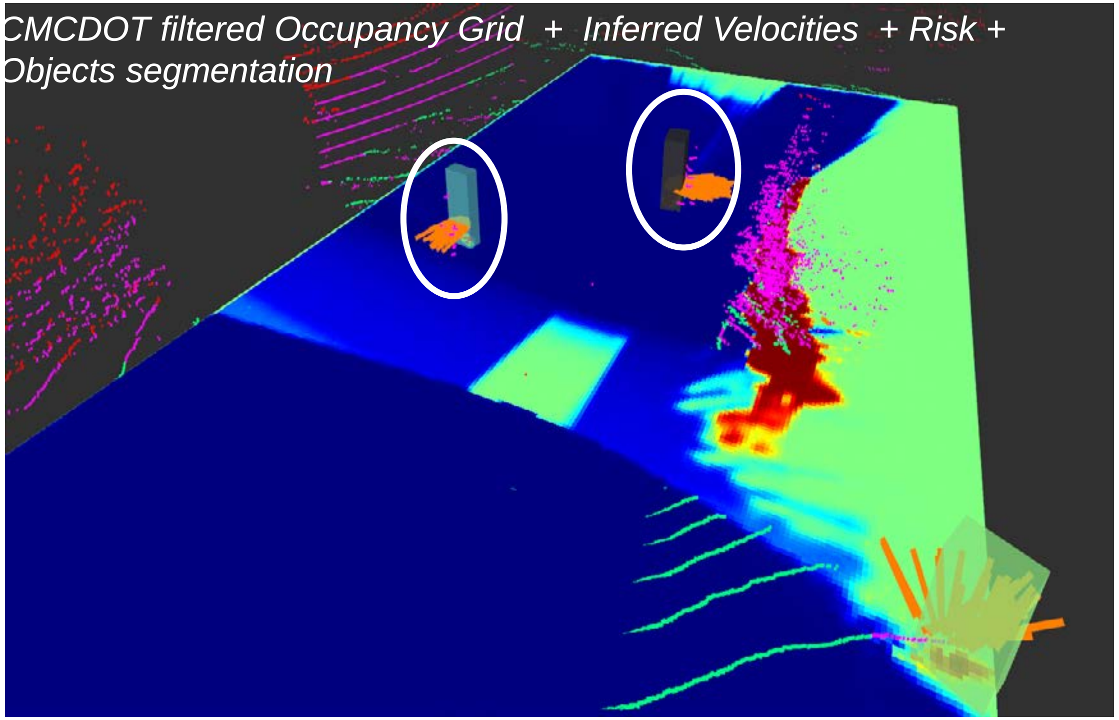
Moving Objects
Detection & Tracking & Classification (2015)

System Integration on a commercial vehicle (2018)

- **POC 2018: Complete system implemented on Nvidia TX1**, and easily connected to the shuttle system network *in a few days* (using ROS)

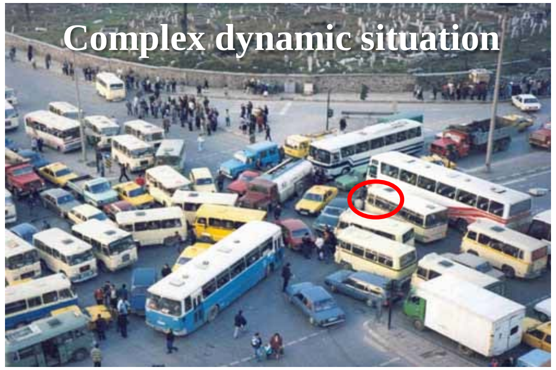
- **Shuttle sensors data** has been fused and processed in **real-time**, with a successful Detection & Characterization of the **Moving & Static Obstacles**
- **Full integration on a commercial product** under development with an industrial company (confidential)





Paradigm 2: Risk Assessment & Decision-making

=> Decision-making for avoiding Pending & Future Collisions



❑ Main challenges

Uncertainty, Partial Knowledge, World changes, Real time

Human in the loop + Unexpected events

❑ Approach: Prediction + Risk Assessment + Bayesian Decision-making

- ✓ *Reason about **Uncertainty & Contextual Knowledge** (using **History** & **Prediction**)*
- ✓ *Estimate **Probabilistic Collision Risk** at a given **time horizon** $t+\delta$ (δ = a few seconds)*
- ✓ *Make **Driving Decisions** by taking into account the **Predicted behavior** of all the observed surrounding traffic participants (cars, cycles, pedestrians …) & **Social / Traffic rules***

❑ Two levels of collision risk have to be considered

- ✓ ***Short-term collision risk** => Imminent collisions, time horizon <3s, conservative hypotheses*
- ✓ ***Long-term collision risk** => Future potential collisions, context & semantics, behavior models*

Concept 1: Short-term collision risk – *Basic idea*

How to deal with unexpected events ? => Exploit previous observations for anticipating a potential future collision

Autonomous Vehicle (Cycab)

Parked Vehicle (occultation)

Pioneer Results (2005)

[PhD Thesis C. Coué 2004]
[Coué & Laugier IJRR 05]

Thanks to the prediction capability of the BOF technology, the Autonomous Vehicle “anticipates” the pedestrian motion and brakes
(even if the pedestrian is temporarily hidden by the parked vehicle)

Short-term collision risk – *Main features*

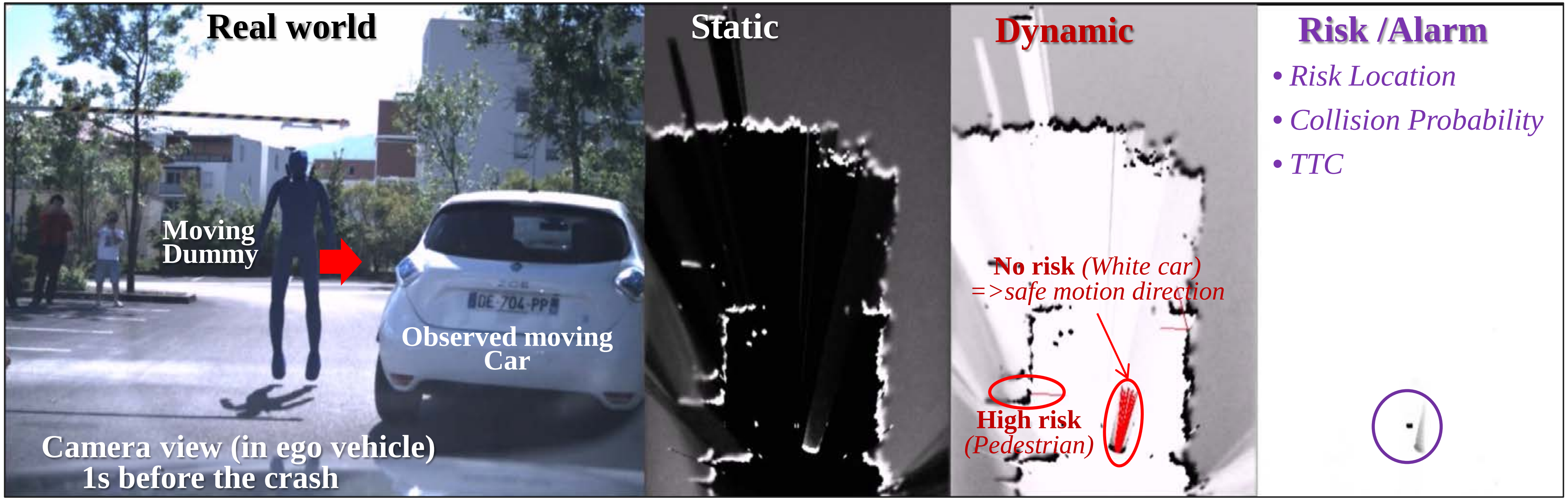
=> Grid level & Conservative motion hypotheses (proximity perception)

Proximity perception: d <100m and t <5s
δ= 0.5 s => Precrash
δ= 1 s => Collision mitigation
δ > 1.5s => Warning / Emergency Braking

❑ Main Features

- *Detect **“Risky Situations”** a few seconds ahead (3-5s)*
- *Risky situations are **both localized in Space & Time***
  - ⇒ ***Conservative Motion Prediction** in the grid (Particles & Occupancy)*
  - ⇒ ***Collision checking** with **Car model** (shape & velocity) for every future time steps (horizon h)*
- *Resulting information can be used for choosing **Avoidance Maneuvers***

❑ System output (real time)



Short-term collision risk – *Experimental results*

⇒ ***Detect potential upcoming collisions***
⇒ ***Reduce drastically false alarms***

Short-term collision risk – *Experimental results (video)*

CMCDOT – Collision Risk Assessment (video – 0:45)

- **Yellow** => *time to collision: 3s*
- **Orange** => *time to collision: 2s*
- **Red** => *time to collision: 1s*

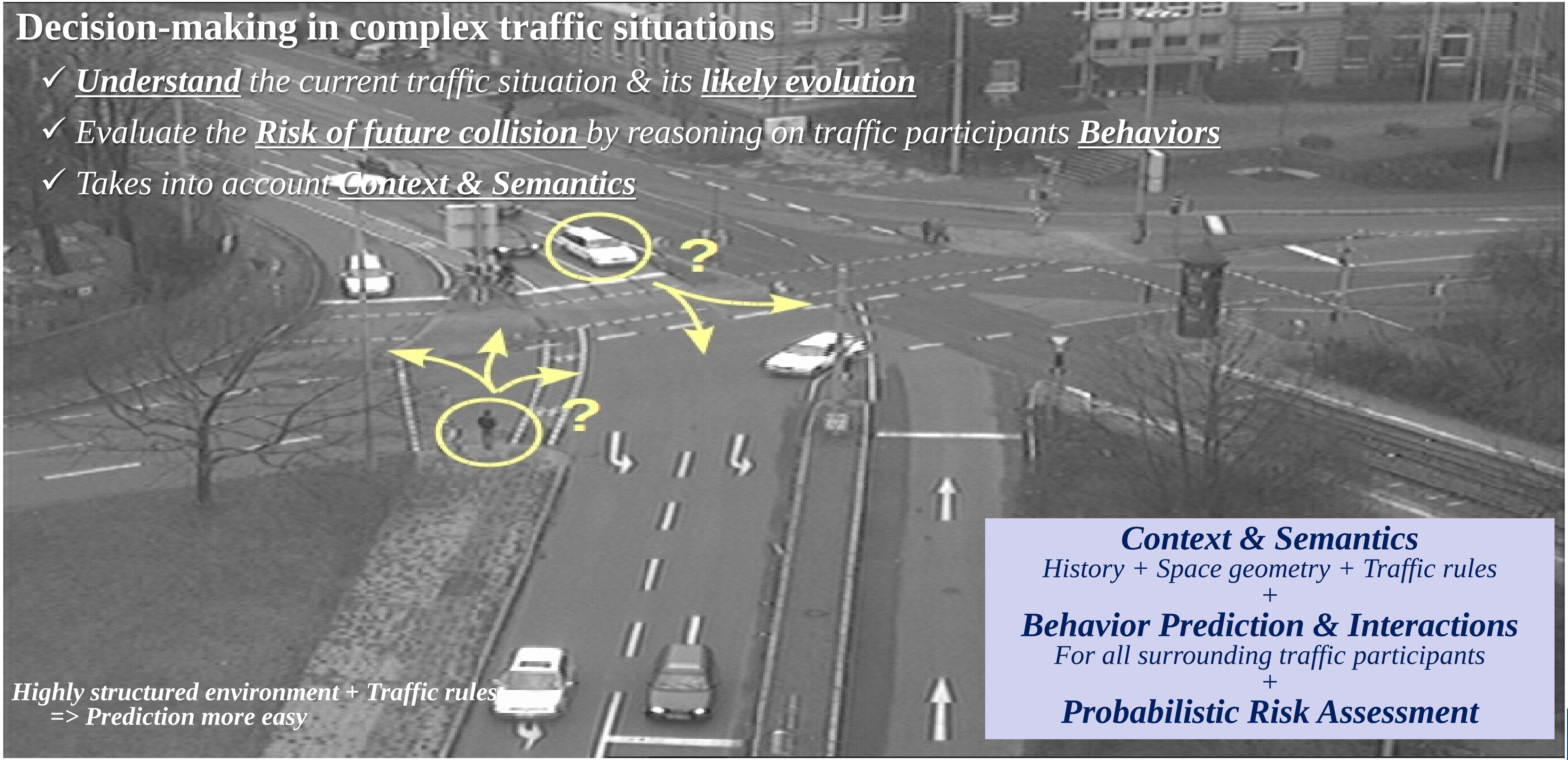
Concept 2: **Long-term Risk Assessment** *(Object level)*

=> Increasing time horizon & complexity using ***context & semantics***

=> Key concepts: ***Behaviors Modeling & Prediction + Interactions***

Decision-making in complex traffic situations

- ✓ ***Understand*** *the current traffic situation & its* ***likely evolution***
- ✓ *Evaluate the* ***Risk of future collision*** *by reasoning on traffic participants* ***Behaviors***
- ✓ *Takes into account* ***Context & Semantics***



Highly structured environment + Traffic rules
=> Prediction more easy

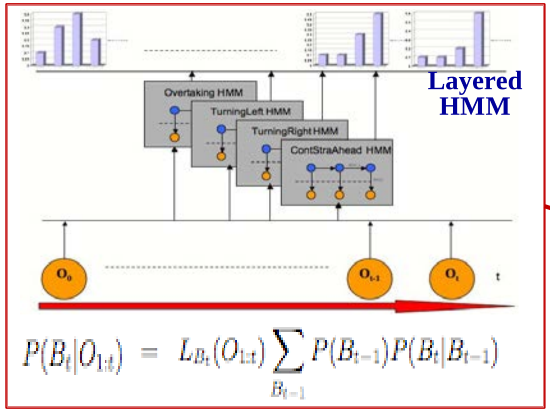
Context & Semantics
History + Space geometry + Traffic rules
+
Behavior Prediction & Interactions
For all surrounding traffic participants
+
Probabilistic Risk Assessment

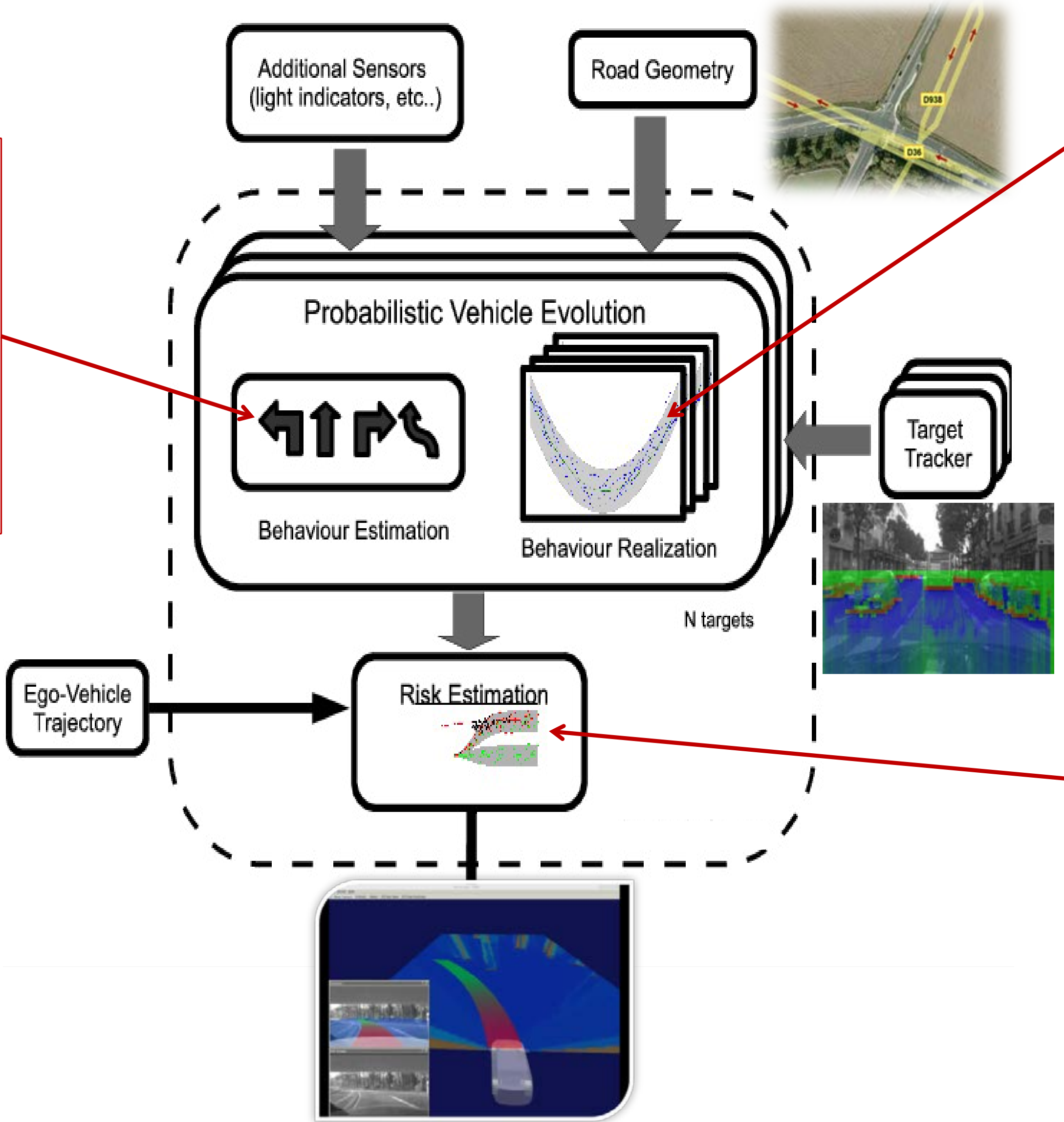
Behavior-based Collision risk *(Object level)*

Approach 1: Trajectories Prediction & Collision Risk Estimation

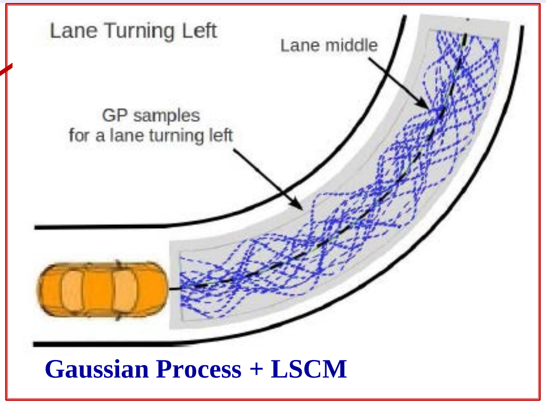
Patent Inria & Toyota & Probayes 2010 + [Tay thesis 2009] [Laugier et al 2011]

Behavior modeling & learning
+
Behavior Prediction

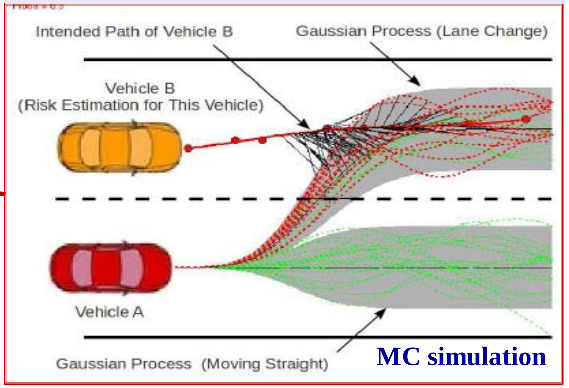




From behaviors to trajectories

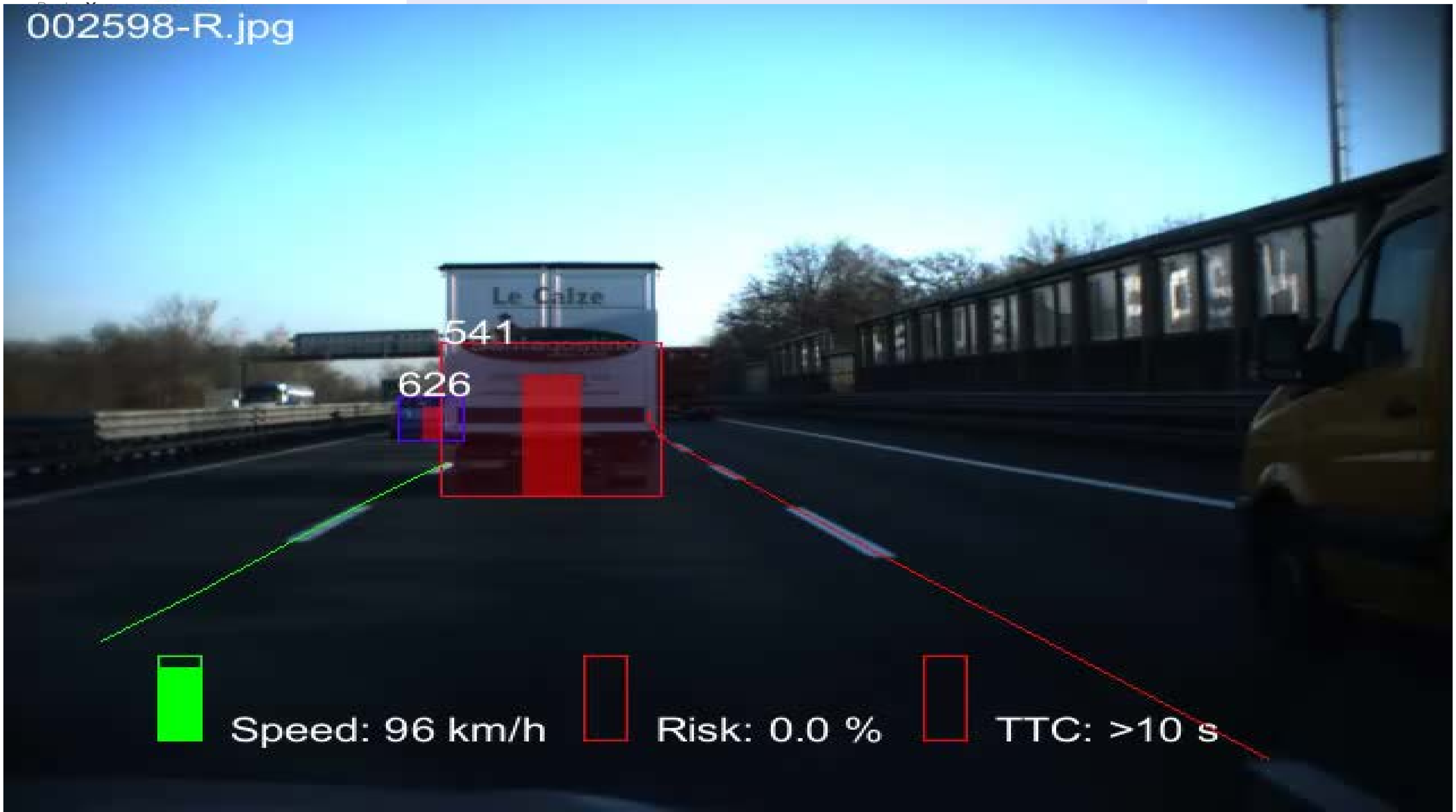


Collision risk assessment
(Probabilistic)



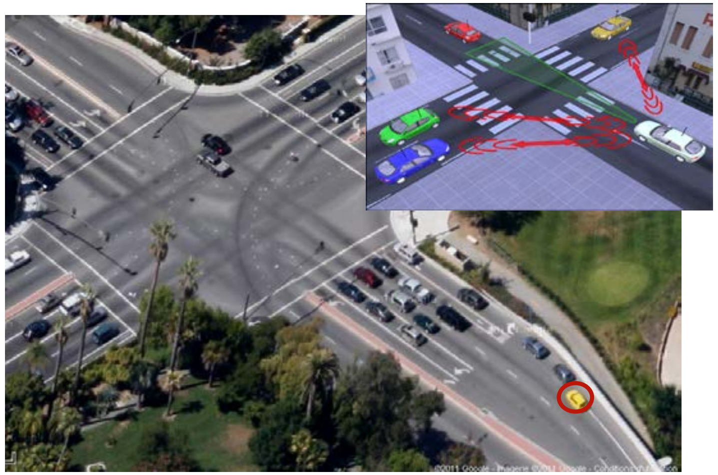
Experimental results: *Prediction Approach 1 – Highways*

Behavior Prediction & Risk Assessment on highway
Video (Courtesy Probayes)



Behavior-based Collision risk *(Object level)*

Approach 2: Intention & Expectation Comparison *=>Interdependent behaviors & Mixed Traffic*

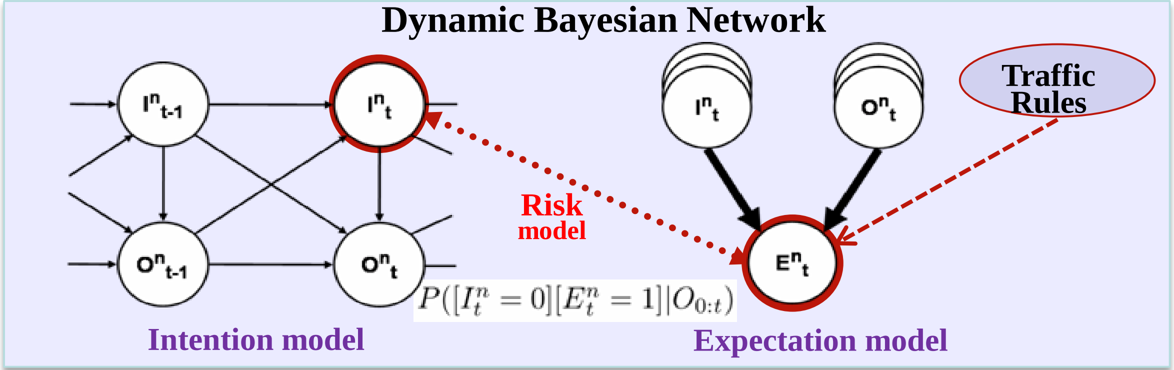


[Lefevre thesis 13] [Lefevre & Laugier IV'12, Best student paper]

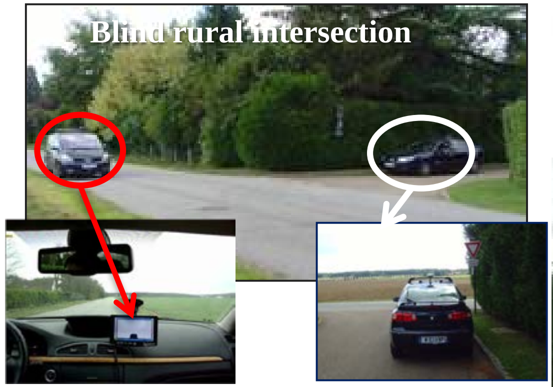
Patent Inria & Renault 2012 *(risk assessment at road intersection)*
Patent Inria & Berkeley 2013 *(postponing decisions for safer results)*

A Human-like reasoning paradigm *=> Detect Drivers Errors & Colliding behaviors*

- ✓ *Estimating **"Drivers Intentions"** from Vehicles States Observations (X Y θ S TS) => Embedded Perception and/or V2X*
- ✓ *Inferring **"Behaviors Expectations"** from Drivers Intentions & Traffic rules*
- ✓***Risk*** = *Comparing Maneuvers **Intention & Expectation***
  - *=> Taking **traffic context** into account (Topology, Geometry, Priority rules, Vehicles states)*
  - *=> **Digital map** obtained using "Open Street Map"*



Experimental results: *Approach 2 – Road intersection & Mixed traffic*



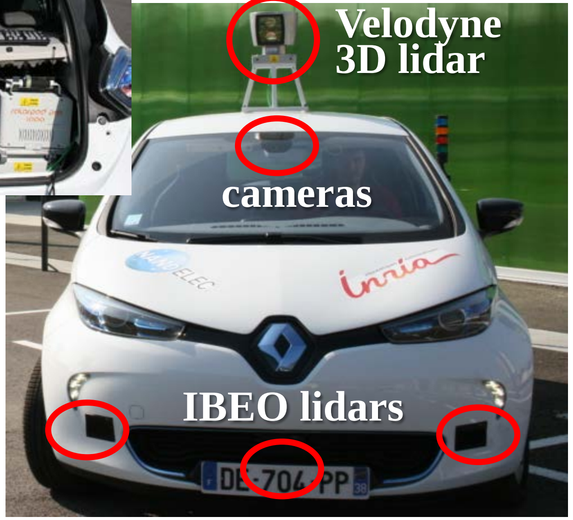
Experimental Vehicles & Connected Perception Units

Toyota Lexus

ROS

RT-Maps
under development

Renault Zoé



Connected Perception Unit (infrastructure)

*Same embedded perception systems than in vehicles => Exchanging only **Collision Risk** information*

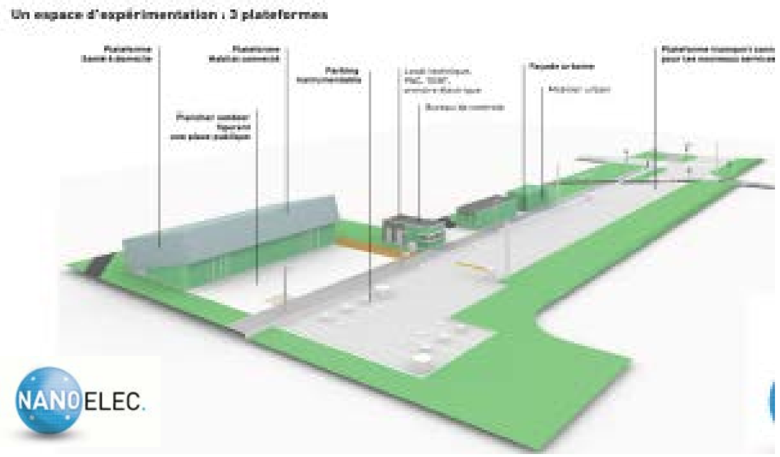
Nvidia GTX Titan X
Generation Maxwell

Nvidia GTX Jetson TK1
Generation Maxwell

Nvidia GTX Jetson TX1
Generation Maxwell

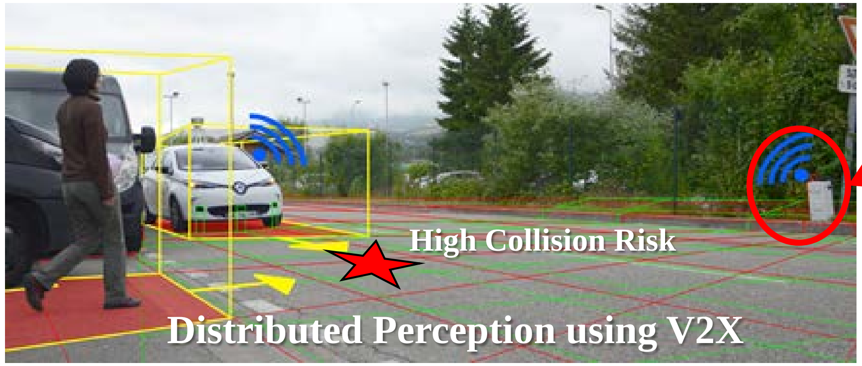
Experimental Areas

- **Protected experimental area** *=> Testing Autonomous Driving L3 & L4*



Crash test track

Connected Perception Unit



- **Open real traffic (Urban & Highway)** *=> Testing Autonomous Driving L2 (ADAS)*

Distributed Bayesian Perception (using V2X)

❑ Data exchange & Synchronization

ITRI

ROS

Broadcast

=> *GPS position + Velocity + Bounding boxes*

Collision Risk (CMCDOT)

=> *Space & Time Localization + Probability*

ITS-G5 (Standard ITS Geonetworking devices)

Basic Transport Protocal IEEE 802.11p

ITRI

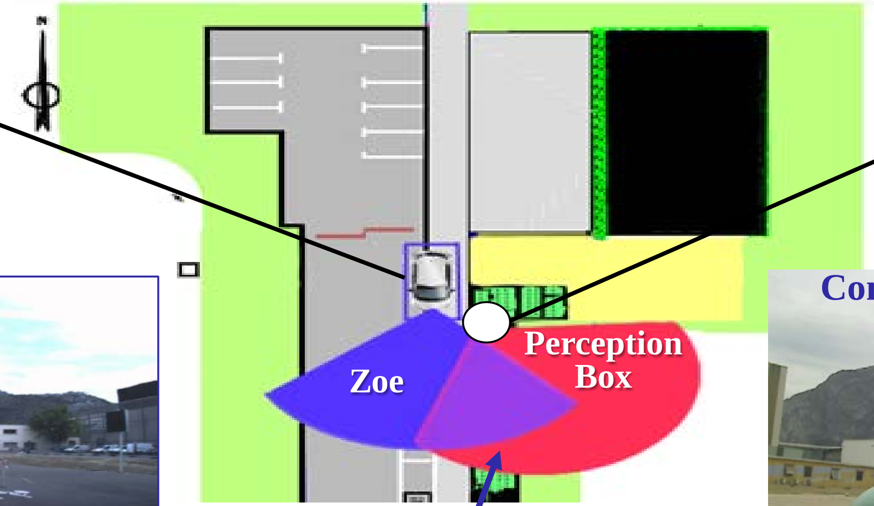
Chrony (**N**etwork **T**ime **P**rotocol)

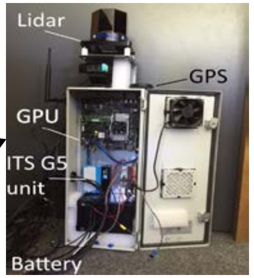
GPS Garmin + PPS Signal (1 pulse per second)

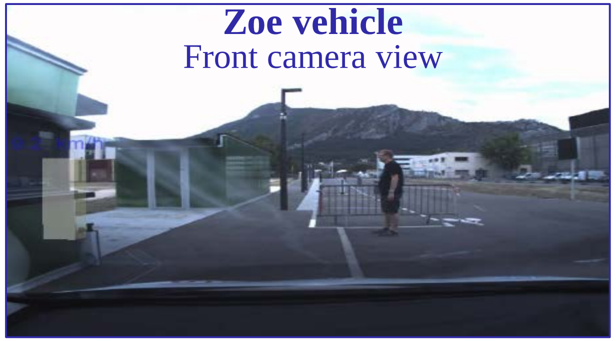
Serial Port

GPIO + UART

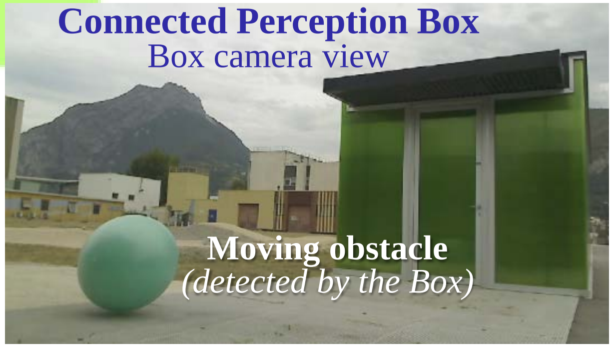
❑ Experimental platform



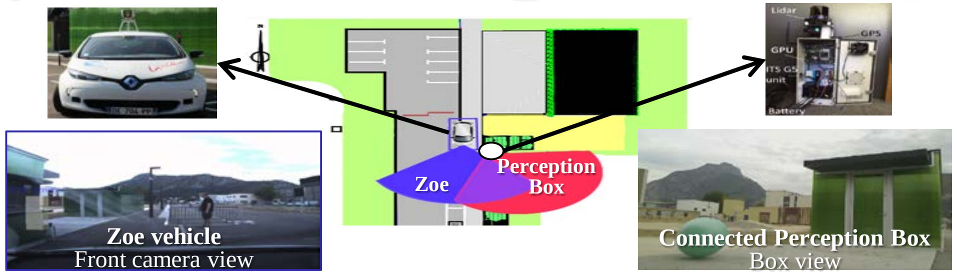


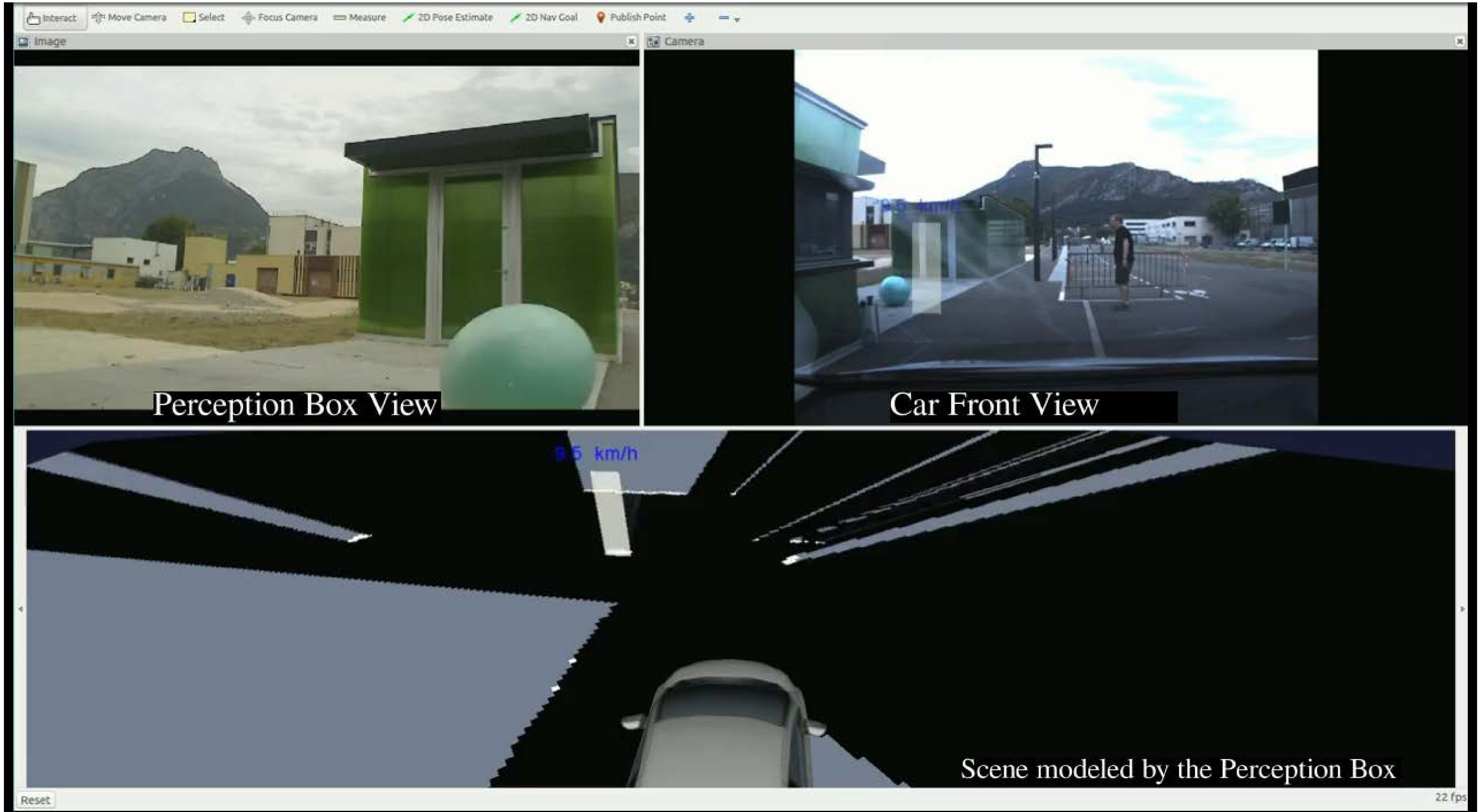


Enlarged Perception Area



Distributed Bayesian Perception – *Experimental results*





On going work

❑ Perception + Decision-making + Control integration

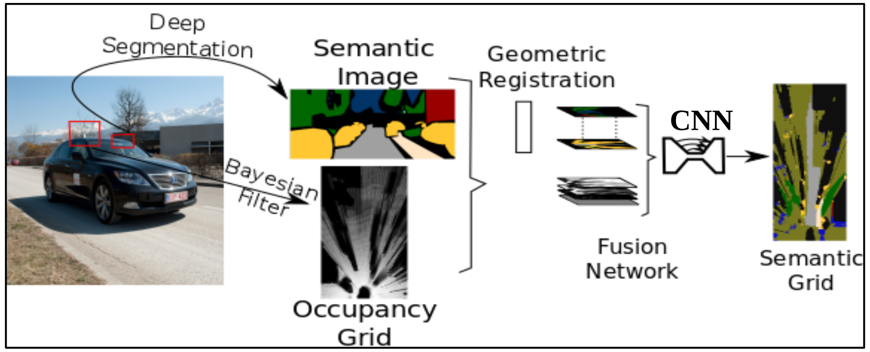
Autonomous Shuttles
(~15 km/h)

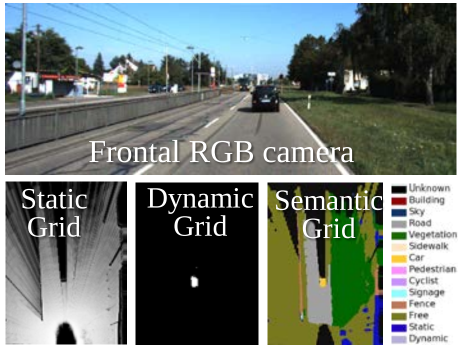
Autonomous Bus (Iveco)
(up to 70 km/h, Urban traffic)

Autonomous Renault Zoe
(up to 70 km/h, Urban traffic)

- Various Dynamics & Motion constraints & Contexts
- Adapted "Collision Risk" & "Collision avoidance maneuvers" (Risk & Maneuver characterization)
- Cooperation IRT Nanoelec, Renault, Iveco …

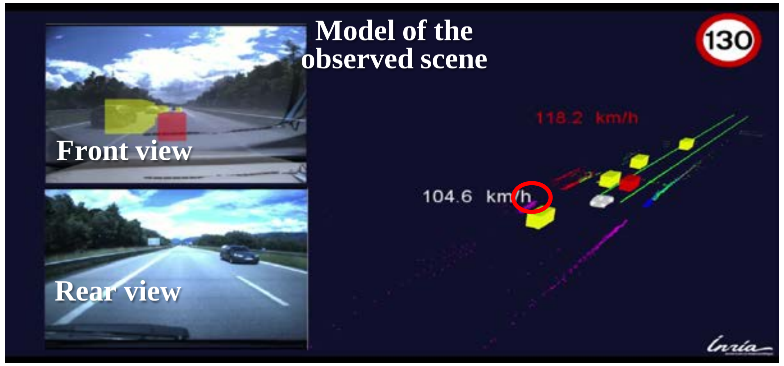
❑ Models enrichment using Semantic Segmentation & Deep Learning





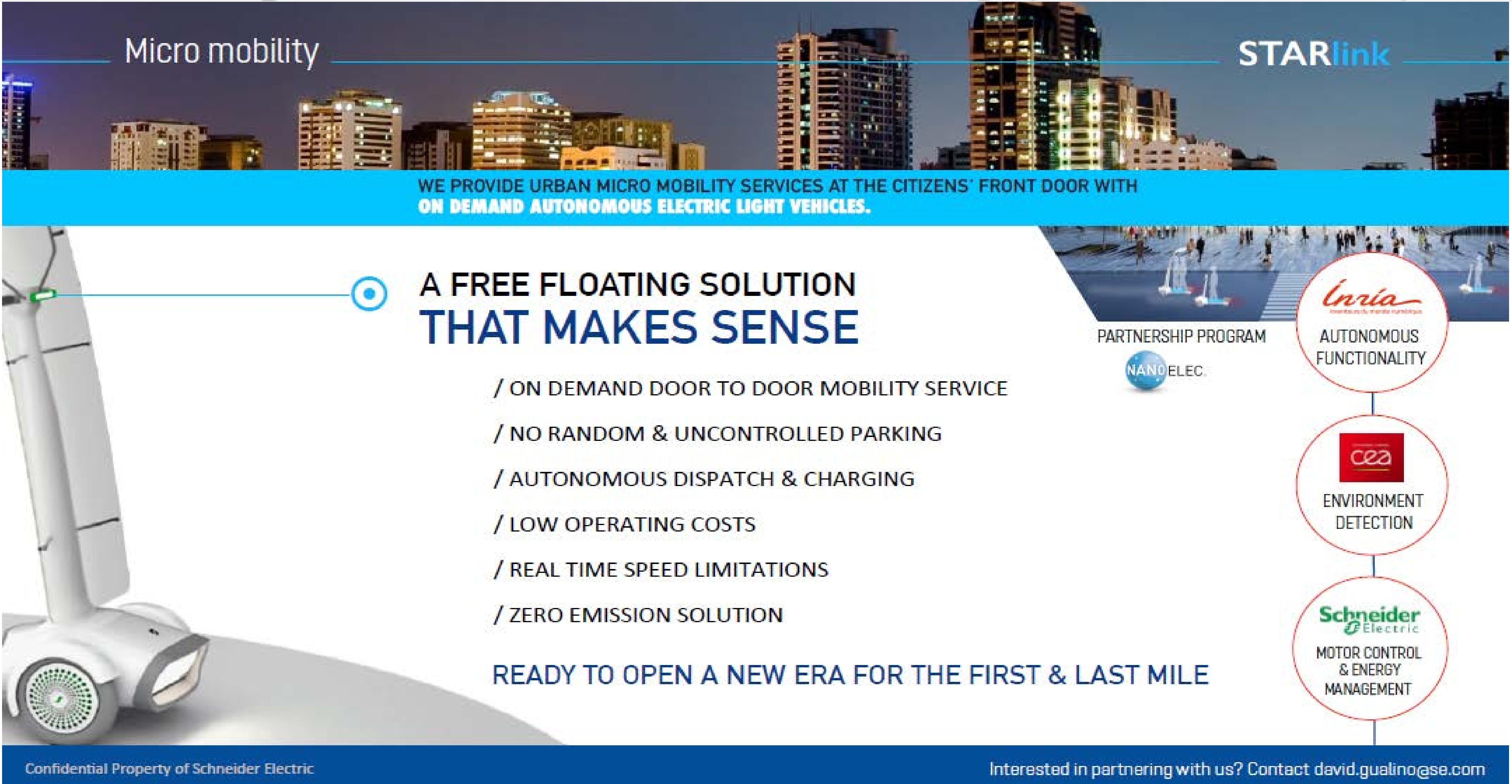
- "Semantic Grids" concept
- Improved scene understanding & decision-making
- Cooperation Toyota
- *1 Patent & 2 publications (IROS'18, ICARCV'18)*

❑ Learning Driving Skills (Prediction & Planning) for Autonomous Driving



- **Driver Behavior modeling** using Driving dataset & Inverse Reinforcement Learning
  *=> **Human-like Driver Model** (for mixed traffic)*
- **Motion Prediction & Driving Decision-making for AD** performed *by combining "learned Driver models" & "Dynamic evidences"*
- Cooperation Toyota
- *2 Patents & 3 publications (ITSC 2016, ICRA 2017, ICRA 2018) & PhD Thesis 2019*

Start-up incubation – *Innovative concept for micro mobility*



Start-up incubation – *Key Features*

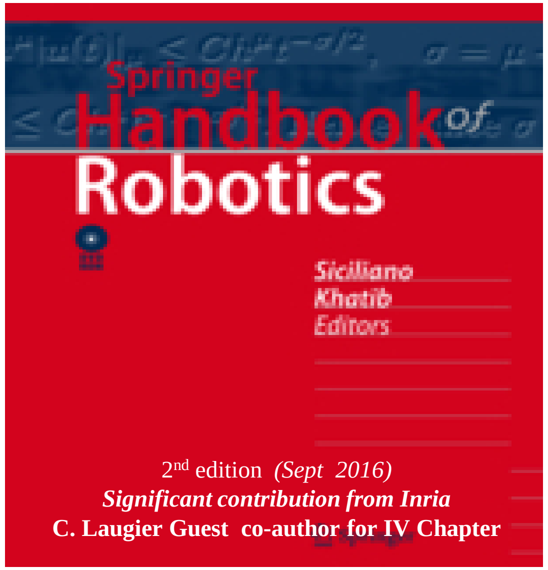
// VALUE PROPOSITION

STARlink

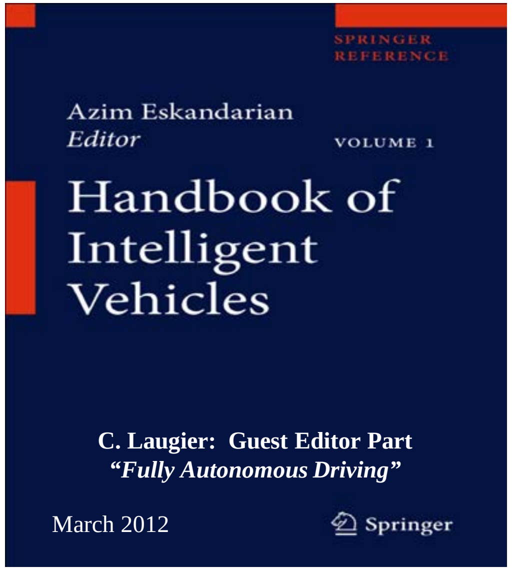
STARLINK provides urban micro mobility services at the citizens' front door with on demand autonomous electric light vehicles.

STARLINK's technology makes mobility operators' life easier and optimize their revenues.

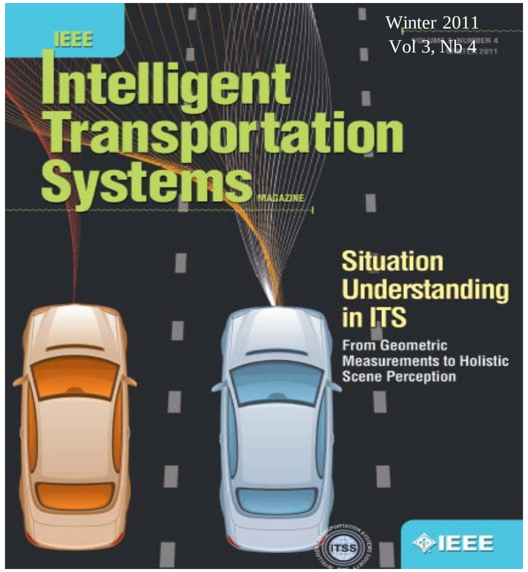
STARLINK's concept provides a clear contribution to environmental issues for better places to live.



2nd edition (Sept 2016)
Significant contribution from Inria
C. Laugier Guest co-author for IV Chapter



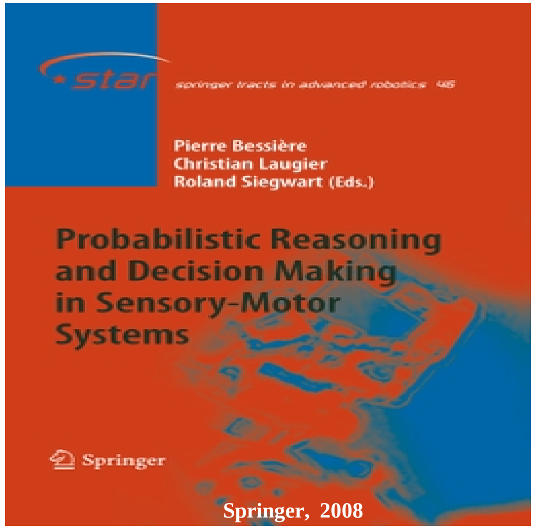
C. Laugier: Guest Editor Part
"Fully Autonomous Driving"
March 2012



Winter 2011
Vol 3, Nb 4

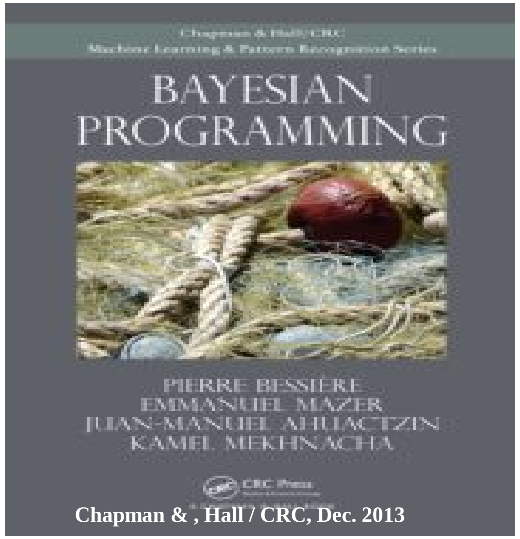
July 2013
Guest Editors:
C. Laugier & J. Machan

Thank You - Any questions ?



Springer, 2008

IEEE RAS Technical Committee on "AGV & ITS"
Numerous Workshops & Special issues since 2002
!! Membership open !!



Chapman & , Hall / CRC, Dec. 2013